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Intra-annual Variability in Benthic Foraminiferal Abundance in Sediments of Disenchantment Bay, an Alaskan Glacial Fjord

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Abstract

Sediment deposited from turbid meltwater from Hubbard Glacier dominates the benthic environment in Disenchantment Bay, a glacial fjord in southern Alaska. Sedimentation rates during the meltwater season average 22 cm yr^{-1} at a station 12 km from the glacier. Samples were collected for foraminiferal analyses from multicores and a piston core. Samples from multicores show annual trends in abundance of *Elphidium* spp. and *Textularia earlandi*. Lithofacies consist of couplets of laminated mud deposited by meltwater discharge in summer and diamicton beds deposited as ice-rafted debris during winter. Within mud layers, counts of *Elphidium* spp. and *T. earlandi* increase upcore until the winter diamicton layer, where they are absent to rare. Evidence for this variation in abundance can be seen at depth in the piston core. High C:N ratios (30–90) indicate that carbon flux is from refractory, terrestrial sources rather than labile organic matter. We hypothesize that the pattern of seasonal variation is related to vertical migration of foraminifera toward a preferred sediment depth, then death following reproduction in late summer. Episodic events reduce total abundance, impacting the intra-annual pattern. The high resolution record from an Alaskan glacial fjord can be used to better understand *in situ* foraminiferal ecology.

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Introduction

Holocene fjords with marine-ending glaciers record high-resolution signals of environmental change in sediment records that are especially useful when chronologies can be developed (Leventer et al., 1996; Jaeger, 2002; Maddison et al., 2005). In temperate fjords of Alaska, sedimentation rates are extremely high and glacial processes dominate the sedimentary record. Meltwater discharge and iceberg rafting produce a strong seasonal forcing of sedimentation (Hunter et al., 1996; Cowan et al., 1997, 1999; Cowan and Powell, 2007). Sedimentation rates in glacier-proximal fjord basins are on the order of tens of centimeters per year allowing for ultra high-resolution sampling of this sediment record. To gain insight into the intra-annual variability of the glacial sediment record of high-latitude glaciomarine fjords, we analyzed benthic foraminiferal assemblages in multicores and piston cores from two stations 12 and 14 km from Hubbard Glacier in Disenchantment Bay (DB), Alaska (Fig. 1). Within this basin, deposition of a glaciomarine varve couplet marks each year (Cowan et al., 1997). High discharge of glaciofluvial sediment into the fjord during the summer meltwater period deposits laminated mud, which is interrupted by episodically deposited graded sand beds and iceberg rafted limestones and clast clusters (Fig. 2). During winter months, meltwater discharge from Hubbard Glacier halts and iceberg rafting becomes the dominant sedimentary process depositing a thick, continuous layer of clast-rich

diamicton (Cowan et al., 1997). The distinctive varved sequence forms a chronology within the dominantly terrigenous sediment fill and can be used to interpret foraminiferal abundance with respect to changing ecological conditions.

Few studies have focused on Holocene foraminifera in coastal Alaska (Bergen and O'Neil, 1979; Quintero et al., 1979; Echols and Armentrout, 1980); however, analysis of grab samples showed a reduction in the species diversity between open-marine Yakutat Bay (YB) and glacier-influenced DB (Echols and Armentrout, 1980). Observed taxa were dominated by those typical of high-latitude, glacier-proximal environments (Korsun and Hald, 1998, 2000; Hald and Korsun, 1997; Majewski, 2005; Jennings et al., 2004), including *Elphidium excavatum* f. *clavatum*, *Elphidium frigidum*, *Elphidium subarcticum*, and *Textularia earlandi* (Appendix). The purpose of this study is to describe variations in benthic foraminiferal abundance within fjord sediment on an annual time scale. Analyzing the resulting trends in a glacier-dominated fjord will aid in understanding subarctic benthic foraminiferal ecology in a stressed environment and in interpretation of marine sediments deposited under glacial conditions.

FIELD SETTING

Disenchantment Bay, a tidewater glacial fjord at the head of YB in southern Alaska, is 5 km wide and 15 km long (Fig. 1). Bathymetry slopes from the glacier to a flat basin floor exceeding

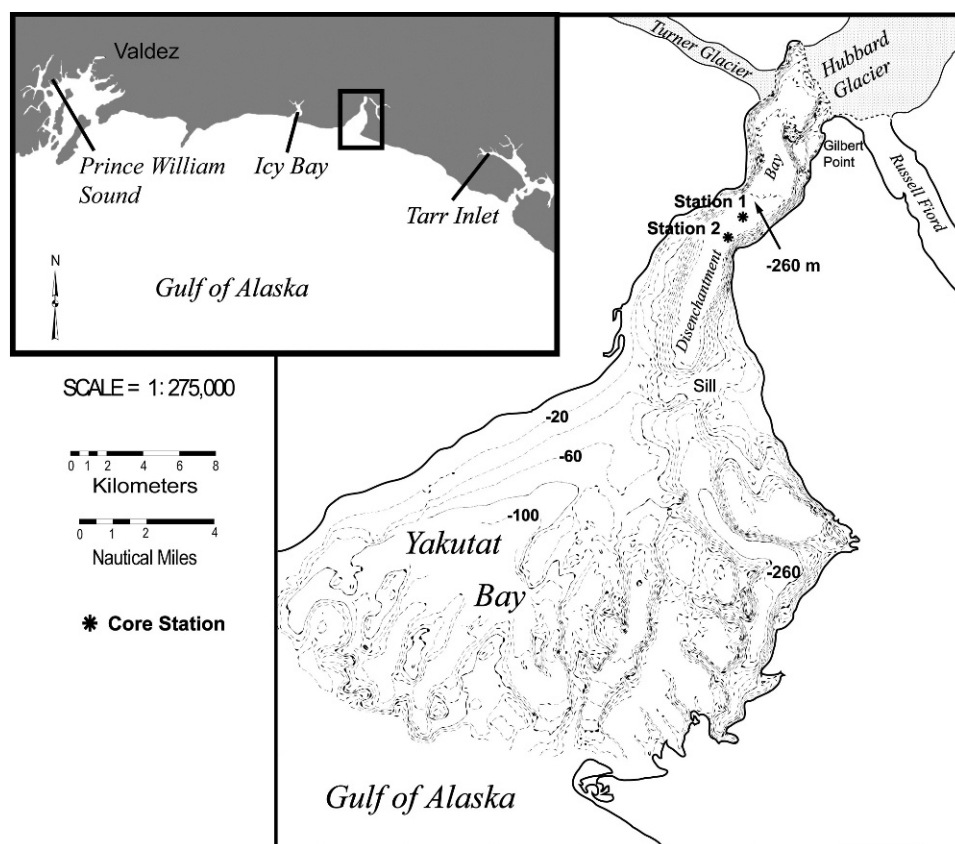


FIGURE 1. Location map of Disenchantment Bay in the northern Gulf of Alaska. Cores AH04-YB PC18, and MC 2-3 (Fig. 2) and 2-6, as well as EW0408 76MC, 72TC, and 72JC, were collected at Station 1. Core AH04-YB MC 1-2 was collected at Station 2.

245 m depth bounded by a bedrock sill that averages 36 m depth in the south, separating DB and YB. In DB, the meltwater plume of Hubbard Glacier generates a low-salinity surface layer where mixing occurs (Curran et al., 2004). At depth, dense, saline water flowing into the fjord basin replaces this surface layer (Curran et al., 2004). The meltwater plume from Hubbard Glacier produces a stratified water column 100 m thick (Curran et al., 2004). Below this surface plume, the water column has a constant density similar to that of ambient seawater (Curran et al., 2004). In basins dominated by glaciers, such as the nearby Alsek River, meltwater produces high discharge from May through August (Deschu et al., 1995). Disenchantment Bay is macrotidal, and strong currents originate near the surface from the entrance to Russell Fiord. This surface water circulation and the mild winter temperatures keep the bay from freezing over in winter.

Hubbard Glacier extends 122 km from the Yukon Territory into DB with an 11.4-km-wide calving face, and has been continuously advancing, periodically abutting Gilbert Point (Trabant et al., 2003). This has resulted in the temporary damming of adjoining Russell Fiord in 1986 and 2002, followed in both instances by outburst floods that are recorded in basin sediments of DB by thick, graded beds of coarse sand and massive fine-grained mud beds (Mayo, 1989; Cowan et al., 1996).

Methods

Cores analyzed for foraminiferal abundance were collected from two stations on the basin floor of DB. We retrieved sediment aboard the R/V *Alpha Helix* in June 2004 using both multicorers and piston corers. In September 2004 we collected additional multicorers and jumbo piston cores with associated trigger cores aboard the R/V *Maurice Ewing*.

MULTICORES

The multicoring rig used in this study retrieved eight multicores at each deployment in 0.5-m-long tubes that captured the sediment-water interface, as indicated by the presence of epifaunal and/or shallow infaunal macrobenthos such as shrimp and small worms. One of the multicores from the set of eight was split, described, and subsampled with an ODP-style U-channel (4 cm² cross-sectional area), while two of the remaining multicores were used for sampling. X-radiograph images were made of both whole cores and U-channels. Sediments were consolidated enough that no material was lost upon splitting of the multicore. We obtained samples from multicores by extruding and collecting sediment at 1 cm intervals down to 20 cm, then 2 cm intervals down to 40 cm.

Extruded multicore samples intended for foraminiferal analyses were immediately placed in plastic containers with 4% buffered formalin and rose Bengal stain to determine whether or not foraminifera were living at the time of collection. Samples were washed over a 63 μ m screen, dried, weighed, and examined for foraminifera. The >63 μ m size fraction was used in foraminiferal analysis in environments where water-mass movement and sedimentation is similar to DB (Jennings and Helgadottir, 1994). Jennings and Helgadottir (1994) and Scott et al. (2008) concluded that including size fractions >63 μ m and >45 μ m, respectively, when picking foraminifera yields a more complete assemblage from sediments within tidewater fjords. We split fossiliferous samples with a microsplitter until one tray contained approximately 300 specimens. Specimens were manually picked from each tray and those with a deep red stain in multiple chambers were considered "stained." Agglutinated taxa were wetted with a brush to confirm the presence of stained protoplasm. Specimens were initially identified under a light microscope. SEM photomicrographs of representatives of each genus confirmed the

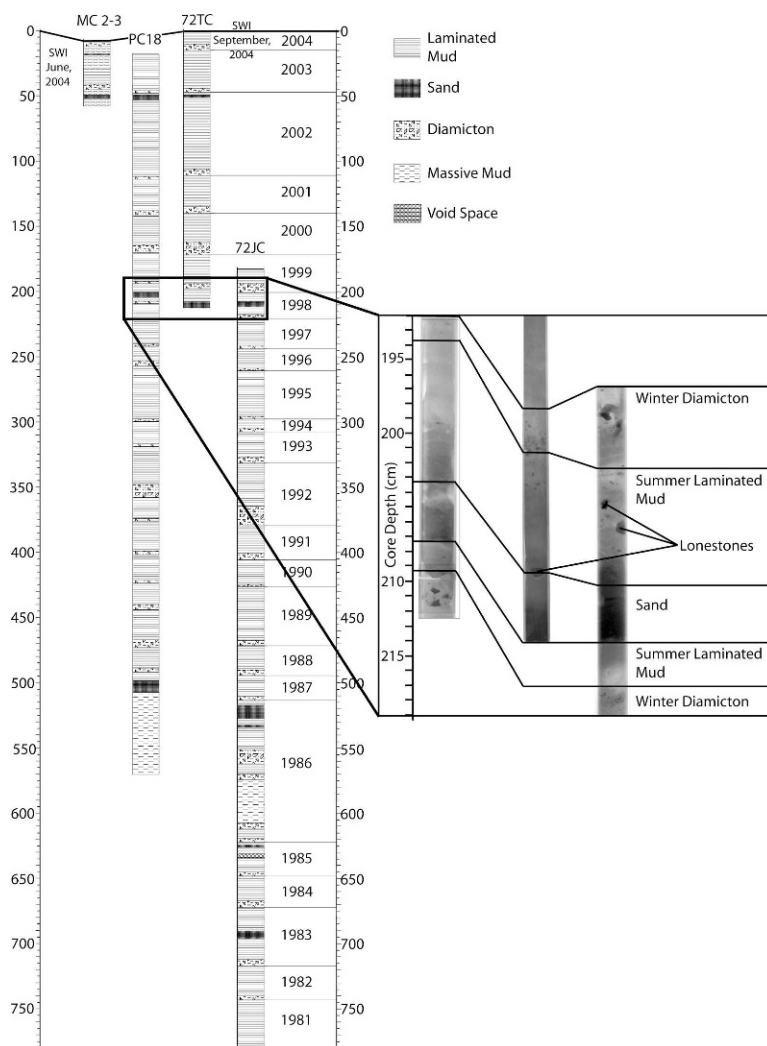


FIGURE 2. Nested core chronology for a suite of cores collected at Station 1. Annual deposition is marked by a winter diamicton and a summer laminated mud. Episodic sand beds (turbidites) appearing in multiple cores were used as datums for stratigraphic correlation. Visual core descriptions, as well as x-radiograph images (inset) were used to distinguish bounds of diamicton and sand beds. SWI indicates the sediment-water interface at time of collection.

identification of foraminifera. Taxonomic notes on species present in DB are available in the Appendix.

Excess ^{234}Th was measured in multicore EW0408 76MC, which was a reoccupation of Station 1 (Fig. 1). Multicores MC1-2 and MC2-6 were collected three months prior to 76MC, resulting in minor differences in stratigraphy due to deposition of summer mud. Activities of ^{234}Th were measured on dried, ground sediment and counted on a low energy germanium detector. The 63.3 keV photopeak was examined to calculate ^{234}Th activities, using the method of Cutshall et al. (1983) to convert from counts per minute (cpm) to disintegrations per minute (dpm). Excess ^{234}Th activities were determined by subtracting supported ^{234}Th activities (determined by recounting the samples after 110 days) from total ^{234}Th activities.

PISTON CORES, JUMBO PISTON CORES, AND TRIGGER CORES

Jumbo piston cores were up to 20 m in length, with 10.2 cm internal diameter, while piston cores collected aboard the R/V *Alpha Helix* were up to 6 m long, with an internal diameter of 7.3 cm. Each of these cores was cut into 1.5 m sections, split, and described. U-channels (4 cm² cross-sectional area) were collected from the center of each core for x-radiograph imaging and measurements of bulk density and magnetic susceptibility. We also collected 10 cm³ samples from intervals within lower-, middle-,

and upper-laminated mud layers of each year, as well as from intervals within several winter diamicton layers in order to determine fluctuations in foraminiferal abundance within each season.

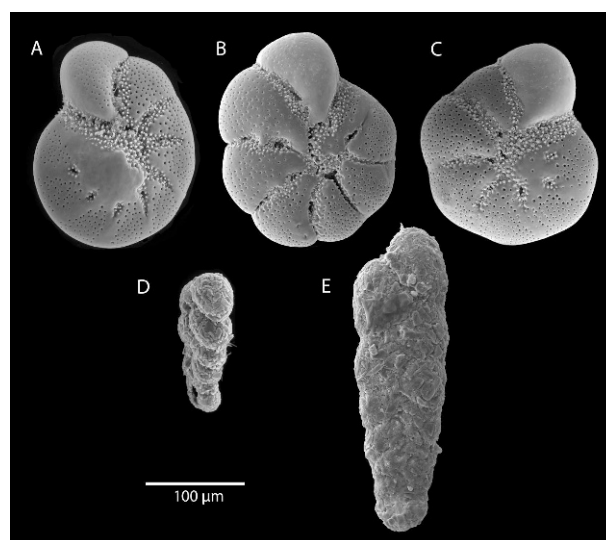
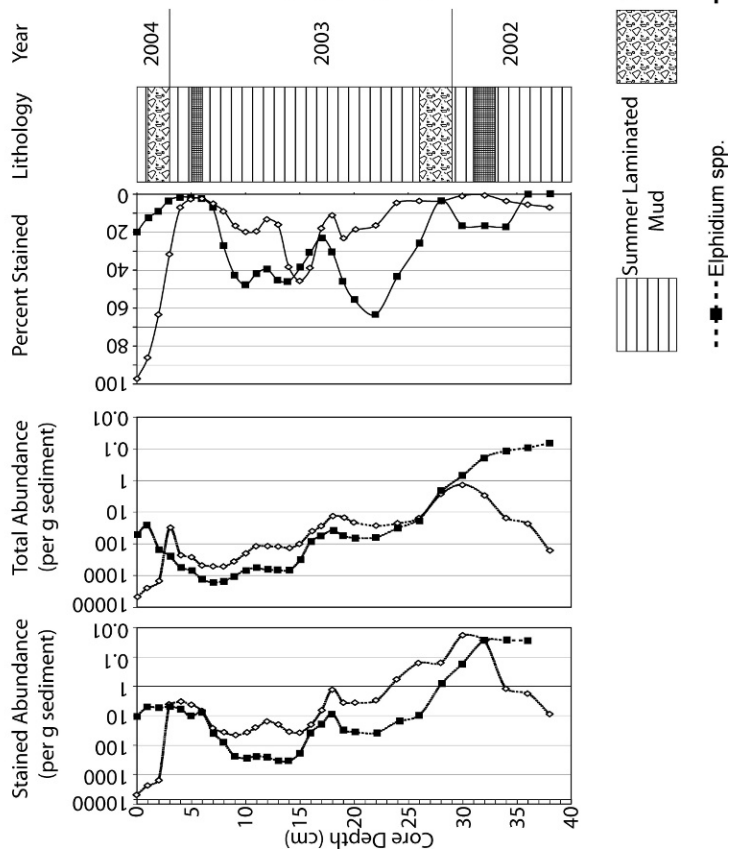


FIGURE 3. SEM Photomicrograph of foraminifera species *Elphidium excavatum* f. *clavatum* (A), *Elphidium subarcticum* (B), *Elphidium frigidum* (C), and *Textularia earlandi* (D, E).

AH04 - YB - MC 1-2

Station 2



AH04 - YB - MC 2-6

Station 1

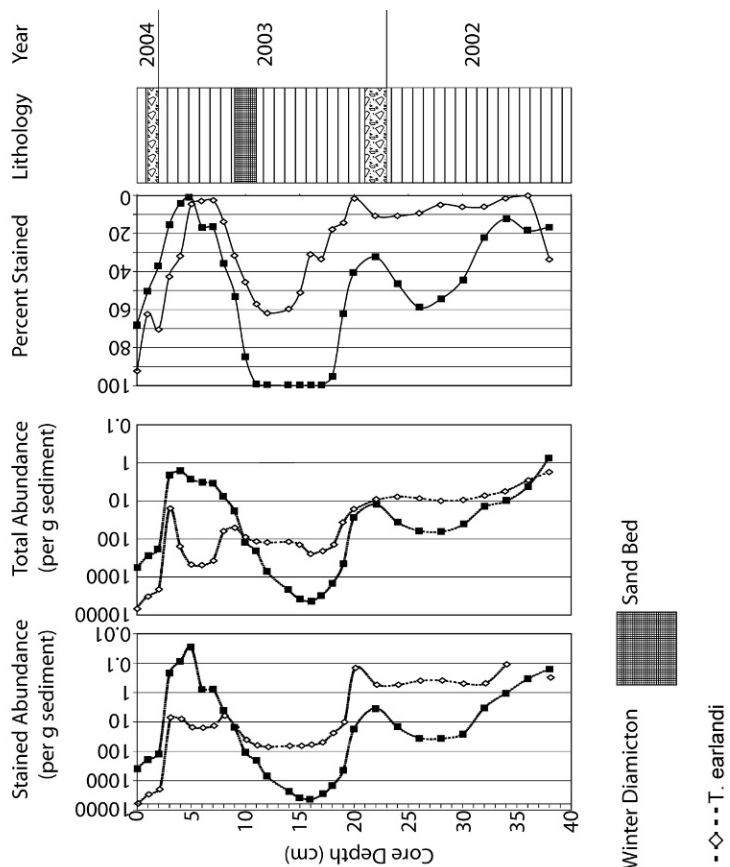


FIGURE 4. Multicores showing a 3-point moving average of stained and total abundance for *Elphidium* spp. and *T. earlandi*. These moving averages are based on raw counts normalized to 1 g of fine-sediment. The percentage of stained individuals relative to total specimens of that taxa is also presented. These percentages are based on the raw abundance counts. Lithology and seasonal interpretation for both multicores are included.

(a, b) Raw species counts from Multicores MC1-2 and MC2-6. Species references are given in Appendix. For the purposes of this study, all counts were normalized to 1 g fine-sediment. Mass of sample examined indicates the amount of material analyzed after splitting of the sample. Abundances were normalized to this mass. Parentheses indicate specimens stained at the time of collection.

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TABLE 1
Continued.

MC2-6	
Sample top (cm)	Sample base (cm)
Mass of sample examined (g)	
Adercotryma glomerata	(7)
Cribrostomoides crassimargo	
Cribrostomoides jeffreysi	
Eggerella advena	
Textularia earlandti	
Agglutinated spp.	
Buccella frigida	
Cassidula spp.	
Cibicides sp.	
Elphidium hannai	
Elphidium spp.	
Epistominella vitrea	
Fissurina spp.	
Isandrella spp.	
Lagena spp.	
Nomionella stella	
Nonionellina labradorica	
Quinqueloculina stalkeri	
Stainforthia sp.	
Calcareous spp.	
Total Benthics	
Globigerina bulloides	
Globigerina quinqueloba	
Globigerinita glutinata	
Neoglobobquadrina pachyderma	
Indeterminate planktics	
Total Planktics	

TABLE 2
Raw species counts from jumbo-core 72JC. All counts used in Figure 5 are normalized to 1 g fine-sediment. Species references are given in Appendix.

EW0408 72JC		Mass of sample examined (g)		Sample top (cm)	Sample base (cm)	Total Planktics	Total Benthics	Indeterminate Benthics	Stainforthia sp.	Reophax sp.	Quinqueloculina stalkeri	Nontionellina labradorica	Nontionella stella	Lagena spp.	Isandella spp.	Fissurina spp.	Epistominella vitrea	Elphidium spp.	Elphidella hannai	Cibicides sp.	Cassidulina spp.	Buccella frigida	Agglutinated spp.	Textularia earlandi	Eggerella advena	Cribrostomoides jeffreysi	Cribrostomoides crassimargo	Bulinna sp.	Adercotryma glomerata	Neoglobobulimina pachyderma	Globigerinita glutinata	Globigerina quinqueloba	Globigerina bulloides	Total Benthics	Indeterminate planktics	Total Planktics																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
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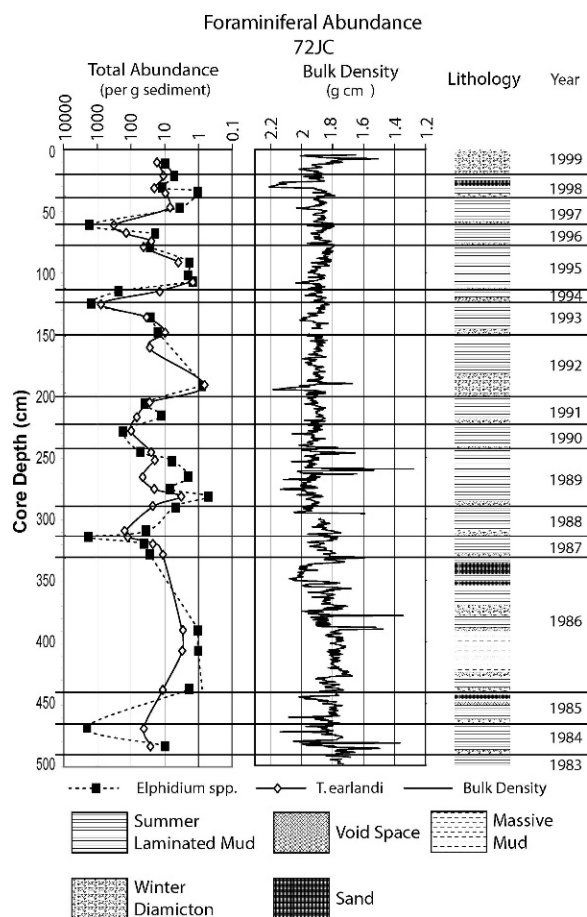


FIGURE 5. Jumbo core (EW0408-72JC) with total abundance of *Elphidium* spp. and *T. earlandi* normalized to 1 g fine-sediment, bulk density, core lithology, and chronology.

Along with each jumbo piston core, a gravity core of 10.2 cm internal diameter was used as a trigger for the piston core release. These trigger cores captured the sediment-water interface, along with approximately 2 m of sediment. Sampling methods of trigger cores were identical to those for jumbo piston cores.

Samples collected from jumbo and trigger cores for foraminiferal analyses were dried, weighed, and soaked in Calgon

disaggregating solution, then wet-sieved over a 63 μm screen. The samples were then processed and picked as described above for the multicores, with the omission of rose Bengal staining.

We determined chronology by counting varves from a nested set of multicores (76MC), a piston core (PC18), a jumbo piston core (72JC), and the associated trigger core (72TC), all collected from Station 1 (Fig. 2), and by tracking seasonal changes in upper sediment with ^{234}Th . The sediment-water interface captured by the multicore and trigger core provided a datum from which we developed a composite depth scale and counted backward (in years) using diamicton beds as annual boundaries. X-radiographs were used to identify the contacts between the laminated mud and diamicton layers because of the density contrast between gravel, sand, and mud. These images were also used to identify distinct deposits of known events, such as the 1986 and 2002 outburst flood turbidity current deposits (Fig. 2). The presence of fine scale silt laminae on x-radiographs within summer layers suggests that bioturbation is minimal to absent within DB. These cores could be correlated with the piston core and jumbo piston core (which commonly blow off an indeterminate interval of sediment during coring) using diamicton and turbidite beds, bulk density, and magnetic susceptibility.

Results

FORAMINIFERAL ASSEMBLAGE

The foraminiferal assemblage observed in cores collected at both stations was consistent with those typical of subarctic, high-sedimentation environments (Fig. 3) (Hald and Korsun, 1997; Korsun and Hald, 1998, 2000; Gustafsson and Nordberg, 2001; Majewski, 2005). *Elphidium* spp. and *Textularia earlandi* were the most abundant taxa (97% of the total population in each sample) and exhibited the most intra-annual variability (Fig. 4). *Buccella frigida*, *Quinqueloculina stalker*, and less common calcareous and agglutinated taxa accounted for less than 3% of the populations observed in both multicore and jumbo core samples (Tables 1a, 1b, and 2). These species were not abundant enough to show clear trends in either jumbo core or multicore data. Raw counts of foraminifera have been normalized to individuals per gram sediment based on the number of individuals counted and the total mass of the sample from which they were picked. The results of this study are

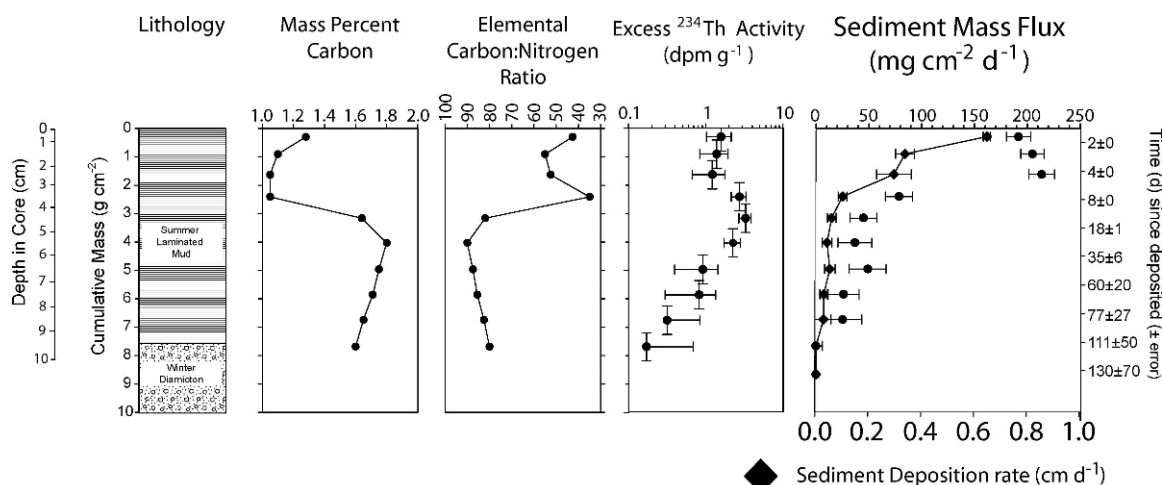


FIGURE 6. Sediment mass flux, bulk sediment carbon to nitrogen concentrations, and ^{234}Th activity at Station 1 (76MC) during one full year. Error bars in radioisotope activity represent the total uncertainty in gamma spectroscopic measurements, and the error in mass fluxes represents propagation of the 5–10% uncertainty in activities into time units (days since core collection).

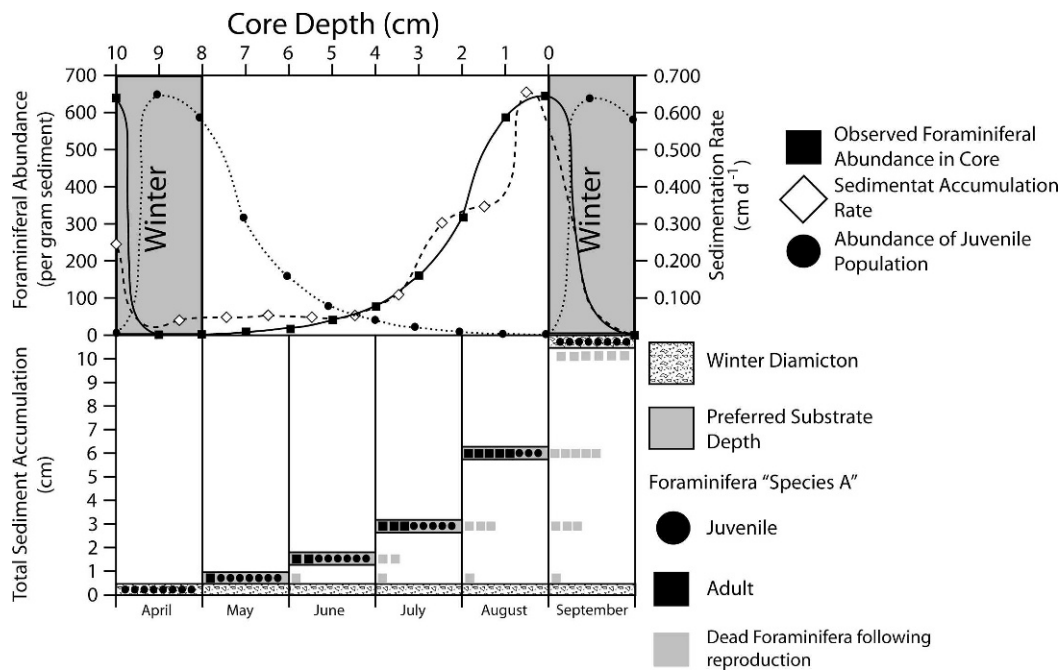


FIGURE 7. Schematic model of foraminiferal migration and development relative to sedimentation rate during the four month long meltwater season in Disenchantment Bay. (A) Sedimentation rates and foraminiferal abundance are based on ^{234}Th chronology and counts from multicores. Abundances observed in the core parallel the increasing population of reproducing adults throughout the meltwater season. (B) This conceptual diagram depicts the migration near the sediment surface of both juvenile and reproducing foraminifera as sediment accumulates to produce the observed intra-annual variability. Within winter seasons, populations consist predominantly of juvenile individuals and very few preserved tests. Later in the meltwater season (September), reproducing adults replace the juvenile population, undergo a reproduction event, and produce a subsequent juvenile population.

presented on a logarithmic scale in order to better visualize the variations in abundance, which ranges from nearly zero to several thousand individuals per gram sediment.

STAINED FORAMINIFERA

Rose Bengal stain was used to document the occurrence of living foraminifera at both the sediment water interface and within the sediment. Approximately 90% of the specimens in surface samples were stained (Fig. 4). Marine worms and other macrofauna were observed moving in the top sample in each multicore, suggesting that the sediment-water interface was sampled intact. Stained foraminifera in the uppermost part of the multicores were probably living at the time of sampling. Stained benthic foraminifera occur at depth in the multicores, but their significance is not straightforward. Zellers and Cruz (2006) initially interpreted these as being infaunal; however, additional work showed the presence of stained planktic foraminifera suggesting that the stain was picked up by undecayed protoplasm. This is consistent with the high sediment flux in this area (see below) and experimental results showing that foraminiferal tests can retain undecayed protoplasm for months after death (Bernhard, 1988; Murray and Bowser, 2000). Nevertheless, counts of stained (with protoplasm) and unstained (empty) tests are both recorded (Tables 1a and 1b) because their variations provide insight into the intra-annual variability of these assemblages.

FORAMINIFERAL ABUNDANCE IN MULTICORES

Lithologic variation and distribution of stained vs. unstained *Elphidium* spp. and *T. earlandi* as well as percent stained specimens are shown in Figure 4. A 3-point moving average of foraminiferal

counts normalized to 1 g of sediment (Tables 1a and 1b) emphasizes upcore trends in foraminiferal abundance.

Multicore 1-2 (MC1-2) exhibits trends in abundance for both *Elphidium* spp. and *Textularia earlandi* abundance in both the stained and unstained fraction (Table 1a, Fig. 4). Significant increases in abundance can be seen from 30 to 22 cm and 18 to 14 cm. *T. earlandi* and *Elphidium* spp. show an increasing abundance throughout the summer laminated mud layer of 2003, and maintain a relatively high abundance composed predominantly of stained individuals in late summer from 14 to 8 cm, below a sand bed at 7 cm (Fig. 4). In the interval of laminated mud just above this sand bed from 6 to 3 cm, remains high relative to early summer mud, but is composed predominantly of unstained individuals. Total abundance decreases significantly at the bottom of the winter diamiction, and increases again at the sediment water interface where specimens are dominantly stained. Both the stained fraction and total abundance of *T. earlandi* undergoes a significant decrease from just above the sand bed at 6 cm to 1 cm below the core top, which represents the sediment-water interface. This uppermost sample contains very high numbers of stained *Elphidium* spp. ($\sim 5000 \text{ g}^{-1}$ of sediment, making 80% of assemblage), with moderately low numbers (140 g^{-1} of sediment) of unstained *T. earlandi*. It is likely that the stained *Elphidium* spp. and *T. earlandi* were living at the time of collection and will be discussed below.

The overall trend in MC1-2 within the summer laminated mud layer is an increase in total abundance of both *Elphidium* spp. and *T. earlandi* upcore until late summer, just below the winter diamiction layer (Fig. 4). An episodic event represented by a 1-cm-thick sand bed at 6 cm disrupts the overall trend of increasing abundance. Foraminiferal abundance below the sand bed is high and dominated by stained individuals, while total foraminiferal

abundance above the sand bed exhibits a significant decrease that is dominated by unstained individuals. Relatively high total abundance within late-summer sediment can also be observed with *Elphidium* spp. from 38 to 34 cm, just below another graded sand bed (33 to 31 cm). This sand bed is interpreted to have resulted from a turbidity current because it fines upward from a sharp base to a gradational top. Within the interval occupied by the sand bed, *Elphidium* spp. abundance decreases significantly. The total and stained abundance of *Elphidium* spp. is lowest at the base of the winter diamicton at 30 cm. While foraminiferal abundance tends to decrease within episodic events, the general trend during 2003 appears to be an increase from relatively low mid-winter/early summer abundance, to a high abundance within late summer sediment.

The variation in abundance within summer mud of MC1-2 is also exhibited by MC2-6 (38 to 26 cm; Fig 4). Both *Elphidium* spp. and *T. earlandi* exhibit low total abundance at 38 cm within early summer mud. Total abundance of both taxa increase upcore above this depth, and reach highest total abundance in late summer mud between 28 and 25 cm, just below the next winter diamicton layer. Abundance of both taxa decreases significantly within the winter diamicton, but begins to increase again just above this layer. Both stained and unstained *Elphidium* spp. and *T. earlandi* show a significant increase in abundance from 20 to 16 cm, and maintain a relatively high total abundance just below a graded sand bed representing an episodic event. Similar to those peaks in abundances found just below sand beds in MC1-2, peaks in *Elphidium* spp. and *T. earlandi* abundance are composed predominantly of stained specimens. Abundance of both species decreases considerably at 10 cm, within and just above the sand bed. *Elphidium* spp. maintain a high total abundance from 10 to 5 cm relative to that of early summer mud, but are dominantly unstained specimens. This peak in total abundance at 6 cm occurs just below a significant decrease in total abundance from 4 to 3 cm, at the base of a winter diamicton. Above this interval, stained specimens become increasingly dominant, and reach a peak at the sediment water interface. Total abundance of *T. earlandi* abundance, however, continues to decrease within late summer sediment above the sand bed until reaching a low in late summer sediment at 4 cm, just below the winter diamicton. The relative abundance of stained individuals also decreases within this same interval, indicating the presence of empty tests within late summer mud.

In both multicores, foraminiferal abundance reaches a peak of predominantly stained individuals at the sediment-water interface. An exception to this is *T. earlandi* abundance in MC1-2, which shows a slight increase at the sediment-water interface. Variations of foraminiferal abundance observed in the multicore data suggest that within a typical meltwater season not exhibiting any episodic events, abundance of *Textularia earlandi* and *Elphidium* spp. increases, reaching peak abundance within late summer sediment that is dominated by unstained individuals. Peaks in abundance are also evident just below episodic events, such as turbidity currents, but are dominated in these cases by stained individuals.

FORAMINIFERAL ABUNDANCE IN JUMBO PISTON CORES

We analyzed 40 samples from a jumbo piston core (EW0408 72JC) corresponding to the period between 1984 and 1998 in order to determine if the annual trends in foraminiferal abundance observed in the high resolution multicores are preserved in the sedimentological record (Fig. 5). Variations in foraminiferal abun-

dance at several intervals within the jumbo core exhibit similarities to higher resolution trends observed in multicores, specifically, foraminiferal abundance in 1987, 1993, 1995, and 1996. Within these intervals, abundance is lowest in early summer sediment just above the winter diamicton, exhibits an increase at the midpoint of each summer mud layer, and reaches a peak just below the diamicton layer of the next year. Other intervals that likely exhibit variations in abundance matching those within the multicores occur in years 1984, 1990, and 1992. A lower sampling resolution within these intervals makes establishing exact trends in abundance difficult, but counts appear lowest in early summer and reach a peak within late summer sediment, just below winter diamicton layers (Fig. 5). The overall decrease in abundance throughout the summer meltwater season observed in years 1985, 1988, 1994, and 1997 is attributed to the low sample resolution collected within these years (some consisting of only one data point).

In addition, foraminiferal abundance within 1988 sediment is lowest in early summer mud and reaches a peak midway through the summer meltwater interval, just below a sand bed. Above this sand bed, foraminiferal abundance exhibits a relative decrease. This variation in abundance is similar to those observed in multicores over intervals spanning sand beds (Fig. 4).

X-radiograph images along with visual descriptions suggest the presence of the 1986 outburst flood deposit from the Russell Fjord between 439 and 330 cm. Above this deposit, 1987 sediments exhibit a distinguishable variation in foraminiferal abundance increasing throughout summer mud layers, and reaching a peak just before winter diamicton. This trend is consistent with those observed in multicore data, as well as other years within the jumbo core. Below 1987 sediments, however, foraminifera are absent, except for two individuals of *Elphidium* spp. at 390 and 405 cm. An increase in abundance from early summer to later summer mud in 1984 sediment suggests that variations in intra-annual abundance are exhibited by sediments below the 1986 flood, disrupted within the flood sediment, and resume above the deposit within 1987 sediment.

SEDIMENT FLUX AT STATION 1

Sedimentation rates of the summer meltwater deposits can be measured over several temporal time scales by different methods. Short-lived radioisotopes can be used to estimate deposition over a large part of the meltwater season while varve counting can indicate annual deposition over the cored interval. At Station 1, complete varves can be identified in 72TC and JC for 22 years between 1983 and 2003 and summer layer thickness can be directly measured. The average thickness over the 20-year period is 22 cm yr⁻¹. The two years during which the outburst floods from Russell Fjord occurred (1986 and 2002) have unusually thick varves that include the episodic flood deposits. These were excluded from the calculation of average varve thickness.

The short-lived radioisotope ²³⁴Th (t_{1/2} = 24 days) was used to establish chronologies and mass fluxes (Jaeger, 2002). Because porosity changed significantly over the upper 5 cm, excess ²³⁴Th activity is plotted against cumulative mass; however, a separate equivalent cm-scale depth axis is provided (Fig. 6). Multicore 76 (EW0408 76MC) did not have steady sedimentation as reflected in the depth-varying activity profile. The lack of bioturbation in the upper 10 cm of core 76MC indicates that the behavior of excess ²³⁴Th activity was due solely to sedimentation. The fluctuating excess ²³⁴Th activity over the 100 days previous to multicore collection, with depth observed in this core, indicates that a steady-state deposition rate could not be calculated (Jaeger, 2002).

Consequently, the Constant Rate of Supply (CRS) method (Appleby and Oldfield, 1992; Robbins, 1978) was used to determine time-varying sediment deposition and mass flux rates (Jaeger, 2002). The results of this method are shown in Figure 6 and reveal that the sediment deposition rate was variable at Station 1 over the previous 100 days, ranging from 0.1 to 0.6 cm day⁻¹ over the upper 10 cm. The deposition rates increased exponentially over the 60 days (August/September) prior to core collection, corresponding to the observation that sediment discharge from Alaskan tidewater glaciers is highest during the late summer meltwater season, which occurs from approximately early August through September (Cowan and Powell, 1991).

Elemental ratios of total carbon to total nitrogen (C/N) were analyzed from bulk sediment to determine the influence of labile organic matter to total carbon flux. These values ranged from 35 to 90. Total weight percent concentration of C ranged from 1.0 to 1.8 and was highest at 5 cm. The lowest total C and C/N ratios occurred between 4 and 1 cm.

Discussion

The annual sediment records investigated in this study exhibit low diversity in benthic foraminifera taxa, but show high variability in the abundance of *Elphidium* spp. and *T. earlandi*, two groups that dominate the assemblage. Abundance of these taxa in multicores ranges from nearly absent within diamicton layers to several thousand individuals per gram of sediment within late summer mud and at the sediment-water interface (Fig. 4). This variability also appears at intervals throughout the jumbo core (Fig. 5).

Foraminiferal assemblages found within the jumbo core were consistent with the *Elphidium excavatum*–*Quinqueloculina stalker* biofacies described by Guilbault et al. (2003). Other taxa in the assemblage, such as *Quinqueloculina stalker* and *Cassidulina reniforme*, are typical of glacier-proximal fjord environments (Korsun and Hald, 2000), although abundance observed within jumbo cores from DB were not high enough to yield a repeatable annual pattern. These comparisons with high-latitude, glacier-proximal assemblages in other regions suggest that diagenetic alteration within sediments of DB has not significantly affected assemblages observed in the multicore or jumbo core record.

ENVIRONMENTAL VARIABILITY ON THE SEAFLOOR

Environmental conditions that are most likely to influence benthic foraminiferal abundance include fjord oceanography, flux of organic material, and the fine-grained sediment flux to the seafloor. Movement of water masses has been shown to influence distribution of benthic foraminiferal assemblages within fjords (Qvale et al., 1984). Water mass circulation within a fjord varies depending on basin morphology, but because DB is narrow and bounded by a shallow sill, this circulation is overwhelmed by the strong influence of Hubbard Glacier (Fig. 1). Glacial meltwater discharges from Hubbard Glacier are found at the head of the fjord from surface runoff and subglacial conduits. Within 1 km of the terminus, the meltwater plume is mixed in the upper 100 m; below this pycnocline the water column is uniform and near ambient seawater (Curran et al., 2004). Density profiles show a similar water column structure continuing downfjord (Curran et al., 2004). Near-bottom water column characteristics appear to be governed strongly by sill depth in Alaskan tidewater glacial fjords because mixing by upwelled meltwater produces a thick, strongly stratified overflow plume that isolates the bottom water from

significant deep water renewal on the adjacent shelf (Cowan, 1992). For example, water column profiles collected near Hubbard Glacier within Russell Fiord showed near-constant conditions in bottom temperature, salinity, and dissolved oxygen from April through September (Reeburg et al., 1976). Although temperature has been regarded as the most important environmental factor controlling foraminiferal distribution (Lee, 1974), this parameter varies little near the base of the water column over the summer months.

Total weight percent of carbon varies from 1.0 to 1.8 within multicores and carbon:nitrogen ratios vary from 35 to 90, which is above the Redfield ratio of 5.7 that is indicative of predominantly marine algal sources (Fig. 6) (Meyers, 1997). The high C:N ratio reflects an abundance of older, highly refractory carbon, likely terrestrial, that would be unavailable to foraminifera. Along with low total carbon weight percent, this suggests that the overall flux of labile organic matter to the sediments within the fjord basin is relatively low. A decreased C:N ratio near the end of summer suggests a modest reduction in the input of refractory carbon. At the same time a significantly decreased weight percent of carbon near the end of the meltwater season indicates an increase in terrigenous sediment flux. These two results suggest that the flux of refractory organic matter to the fjord basin near the end of summer is diluted by labile material. A decrease in refractory carbon suggests that availability of food to foraminifera increases during late summer. Food availability is one of the most important factors contributing to foraminiferal abundance, and an increase in labile organic matter supports the likelihood of a late summer reproduction event (Gustafsson and Nordberg, 2001).

Additionally, chlorophyll a was found in a study by Etherington et al. (2007a, 2007b) to remain relatively high during the months of May through September in Tarr Inlet water column, a tidewater glacial fjord in Glacier Bay National Park, southeastern Alaska (Fig. 1). During months of October through April, however, chlorophyll a levels decrease significantly. This observation also suggests that food supply from the water column may be variable and contributes to late summer reproduction.

The high sedimentation rates of DB (Fig. 6) may provide a direct constraint on intra-annual distribution of benthic foraminifera because the taxa present are known to migrate upward in response to rapid sediment flux (Kitazato, 1988). *Elphidium* species typically live on the surface of the sediment, and do not survive well within the substrate (Jorissen, 1999; Wefer, 1975). Other calcareous species burrow very shallowly and move about within the upper 1 cm of sediment, while agglutinated species occur predominantly within the top 5 cm of sediment (Jorissen, 1999; Wetmore, 1988; Gross, 2000; Saffert and Thomas, 1997). Active burrowing of foraminifera has been observed in response to such environmental factors as oxygen concentrations, which may become depleted within a few centimeters of the sediment-water interface, and food availability (Moodley and Hess, 1992; Alve, 1995; Alve and Bernhard, 1995; Murray, 2001). These environmental conditions within fjord sediments provide a limited habitable sediment depth for infaunal foraminifera, and as more sediment accumulates throughout the meltwater season, foraminiferal migration in response to environmental variables is dominantly upward toward the sediment-water interface (Saffert and Thomas, 1997).

In short-term laboratory studies in which sediment depths were held constant, *Textularia* spp. migrate through sediment at an average rate of 46 mm day⁻¹, while *Elphidium* spp. migrate at an average rate of 37 mm day⁻¹ (Kitazato, 1988). Bornmalm et al. (1997) have observed varying migration rates among the agglutinated species *Ammodiscus anguillae* of from 1 to 10 mm

day⁻¹ in response to changing environmental conditions. These data indicate that both taxa observed in DB sediments are theoretically able to maintain a migration rate faster than that of the maximum daily sedimentation rate (Fig. 6). It is likely that because foraminifera in DB occupy a preferred sediment depth within a few centimeters of the sediment-water interface, and that they are able to maintain a vertical migration rate exceeding that of the sediment accumulation rate within the fjord basin, these foraminifera migrate upward through continuous deposition during the meltwater season in order to maintain a suitable depth within the substrate (Fig. 7).

As these foraminifera grow and reach maturity, they undergo a reproductive cycle, dividing into either gametes (sexual) or agametes (asexual; Murray and Bowser, 2000; Gustafsson and Nordberg, 2001). This process leaves the original test devoid of protoplasm, which therefore remains *in situ* as sediment accumulates above it. Foraminifera often reproduce in clusters, resulting in significant peaks in abundance of empty tests (Goldstein, 1999; Murray and Bowser, 2000). The highest peaks in abundance of unstained *Elphidium* spp. and *T. earlandi* in both multicores and jumbo cores occurred within late summer sediment, suggesting that these preserved tests represent reproduction events.

We hypothesize that foraminifera in fjord basin sediments of DB burrow vertically upward through continuous fine-grained deposition until reaching reproductive maturity toward the end of the summer meltwater season, whereupon a reproduction event results in the death and preservation of high numbers of foraminiferal tests. The subsequent juvenile population then migrates vertically upward throughout the next year until reaching reproductive maturity, and so on. This behavior causes low observed abundance within winter diamicton and an increase in observed abundance toward late-summer that is not directly related to population increase, but migratory and reproductive patterns within high-sedimentation environments.

INTRA-ANNUAL REPRODUCTION AND DISTRIBUTION

Both multicores exhibit evidence for this upward vertical migration. These cores (MC 1-2 and 2-6) were collected in early summer (June) and exhibit very high foraminiferal abundance within surface sediments (just above the winter diamicton) as compared to early summer sediment from the previous year (Fig. 4). Several years within the jumbo core also exhibit low abundance within early summer sediment (Fig. 5), suggesting that living populations migrate upward, away from winter diamicton as sediment accumulates throughout the meltwater season.

During winter, populations have not yet reached reproductive maturity and are able to sustain migration through deposition of winter diamicton. At the onset of summer mud deposition, the juvenile population migrates upward through continuous fine-grained sediment accumulation, leaving the winter diamicton behind. This behavior would produce a very low observed abundance within and just above winter diamicton. As these populations grow and begin to reach reproductive maturity, more and more individuals would undergo gametogenesis, leaving empty tests buried within laminated summer mud. The increasing number of individuals reaching maturity and undergoing reproduction would produce an increasing abundance of preserved tests within summer laminated mud.

This increasing number of reproducing individuals is preserved within summer laminated mud layers (Figs. 4 and 5) due to the significantly high sedimentation rate, which increases exponentially throughout the meltwater season (Fig. 6). At the end of the

meltwater season, sedimentation rates decrease significantly, and deposition is dominated by coarse-grained, ice-rafted sediment. This decrease in sedimentation would result in the halting of upward vertical migration, and an accumulation of empty foraminiferal tests as more and more individuals underwent reproduction, which would subsequently produce the observed late-summer peak in abundance. This “traffic jam” in foraminiferal migration is not likely the case, however, as an accumulation of abandoned tests during periods of low sedimentation would continue throughout the winter, resulting in a high observed abundance within winter sediment. Peaks in abundance are restricted in most cases to a narrow interval just below diamicton layers, suggesting that a discrete reproduction event occurs near the end of each summer meltwater season, producing a new juvenile population.

Assemblages analyzed within multicores and jumbo cores exhibit low diversity throughout the summer season (Tables 1a, 1b, and 2), dominated by both *Elphidium* spp. and *T. earlandi*. This suggests that intra-annual changes in lateral distribution of assemblages found in DB do not play a significant role in altering the abundances of foraminifera within the fjord basin.

RESPONSE TO EPISODIC EVENTS

In both multicores, intervals of high abundance in both *Elphidium* spp. and *T. earlandi* are present just below thin sand beds deposited in 2003 (Fig. 4). Abundance of *T. earlandi* specimens within these intervals is dominated by stained individuals between 14 and 9 cm. This abundance decreases significantly within and just above the sand beds. Abundance of *Elphidium* spp., however, remains high within and above the sand beds, and exhibits a lower percentage of stained individuals (Fig. 4). High abundance of dominantly stained individuals suggests that turbidity currents rapidly deposited coarse sand which trapped *T. earlandi* populations, while a high abundance of unstained *Elphidium* spp. suggests that these populations were better able to burrow vertically upward and escape unfavorable conditions beneath the sand beds.

Stained foraminifera at these core depths, therefore, do not represent living infaunal populations, but rather specimens retaining preserved protoplasm due to rapid burial. The fact that similar patterns of unstained specimens in MC 1-2 were also preserved below a sand bed suggests that the staining in MC 2-6 also represents undecayed protoplasm in dead foraminifera.

Properties of a suitable substrate for benthic foraminifera include the chemistry of interstitial water and the size and density of pore spaces (Sen Gupta, 1983). A study by Kitazato (1995) has also suggested that foraminifera have particular substrate preferences, which are dependent upon grain size and roundness, as well as compaction of surrounding sediment. The coarse grain size, and rapid compaction of sediment as it accumulates following deposition of a turbidity flow result in conditions unsuitable for habitation by *T. earlandi* populations (Goldstein, 1999). This prevents the population from undergoing a reproduction event at the end of summer in MC 1-2, and the subsequent population at the onset of the 2004 meltwater season is relatively low (sediment-water interface; Fig. 4). *Elphidium* spp. populations, which are typically more tolerant of unfavorable conditions, are able to escape turbidite layers, migrate upward and undergo reproduction at the end of summer in 2003, resulting in a high abundance at the onset of the 2004 meltwater season in MC 1-2. The disparity in migration through coarse sediment layers suggests episodic events may impact assemblage diversity and species dominance at the sediment-water interface from year to year (Fig. 4).

Major episodic events such as the 1986 outburst flood appear to cause foraminiferal abundance to decline abruptly, providing another example of foraminiferal response to a change in preferred sediment depth. Sediment from the outburst flood preserved in jumbo core 72JC revealed 0–2 foraminifera per 1 g of sediment in each sample, whereas above and below the flood layer, populations varied from <10 to >500 individuals. This abrupt decrease in foraminiferal abundance is seen in other fjord settings that experienced episodic events, such as the response of foraminiferal abundance and diversity to a 1996 flood event in Sangueney Fjord (Leduc et al., 2002). Foraminiferal populations in Sangueney Fjord, however, slowly regenerated over a period of two years (Leduc et al., 2002). Foraminifera counts in DB returned to relatively high numbers during the year following the 1986 flood, suggesting that recolonization of foraminifera within this fjord basin occurs rapidly.

In Figure 7, we present a simplified conceptual model of the vertical migration of foraminifera within ice-proximal glacial fjord basin sediment. In this model, foraminifera maintain a high abundance near the surface of the sediment, remaining within a preferred depth range as sedimentation rate increases throughout the meltwater season. Near the end of the summer meltwater season, the majority of the population reproduces, producing a peak in abundance of empty tests, while the new juvenile population begins to migrate upward through winter diamicton deposition. More tests are buried and preserved as more individuals reach reproductive maturity during the next summer meltwater season. This produces an observed increase in foraminiferal abundance near the end of the meltwater season that is not directly related to an increase in population size.

Conclusions

The ice-proximal basin of the tidewater Hubbard Glacier provides an environment in which terrigenous sediment flux dominates environmental variables, controlling abundance of benthic foraminifera. This environment is ideal for studying the intra-annual dynamics of subarctic benthic foraminiferal assemblages. Analyses of samples collected within summer layers show highly variable but repeatable population dynamics of *Elphidium* spp. and *Textularia earlandi*. Both species repeatedly reached peak abundance during the late summer season, in deposits of laminated mud. Timing of the peaks in abundance is most likely controlled by the preservation of reproduction events within accumulating sediments during the meltwater season. Temperature, salinity, and dissolved oxygen content on the fjord bottom do not vary greatly throughout the year, and it appears that more labile organic matter is deposited during the meltwater season, leaving sedimentation as the primary environmental variable affecting distribution foraminiferal abundance. High sedimentation buries foraminiferal populations *in situ*, necessitating upward vertical migration of foraminifera throughout the meltwater season and resulting in death and preservation of foraminifera as they reach maturity and reproduce during late summer. Dominance of stained individuals preserved below episodic events, recorded as graded sand beds (turbidites), indicate that certain species of foraminifera (*T. earlandi*) respond negatively to a rapid influx of coarse-grained sediment while others (*Elphidium* spp.) do not, suggesting that changes in assemblage diversity may be affected by these deposits. Foraminiferal abundance was depleted during the 1986 outburst flood event, but was reestablished the following year. This is similar to the foraminiferal response to flood events in other fjord settings.

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- research was done in separate facilities, we decided to group all the *Elphidium* species together for purposes of this study.

BENTHIC SPECIES

- Agglutinated spp.—this group includes rare specimens of *Reophax* and *Trochammina* and indeterminate agglutinated species.
- Adercotryma glomerata* (Brady, 1878). Loeblich and Tappan, 1953, p. 26, pl. 8, figs. 1–4.
- Buccella frigida* (Cushman, 1922). Todd and Low, 1961, p. 18, pl. 3, fig. 25.
- Calcareous spp.—this group includes rare specimens of *Bolivina*, *Cornuspira*, *Dentalina*, *Discorbis*, *Guttulina*, *Quinqueloculina*, and *Triloculina*, and indeterminate.
- Calcareous species.
- Cassidulina* spp.
- Cibicides* sp.
- Cribr stomoides crassimargo* (Norman, 1892). Echols and Armentrout, 1980, p. 297, pl. 2, figs. 7–8.
- Cribr stomoides jeffreysi* (Williamson, 1858). Echols and Armentrout, 1980, p. 297, pl. 2, figs. 5–6.
- Eggerella advena* (Cushman, 1922). Cushman, 1922, p. 59, pl. 1, figs. 7–9.
- Elphidiella hannai* (Cushman and Grant, 1927), Echols and Armentrout, 1980, p. 295, pl. 1, figs. 1–2.
- Elphidium* spp.—this group includes:
- Elphidium excavatum* (Terquem, 1876) f. *clavatum*, Buzas, Culver and Isham, 1985, pp. 1083–1084, pl. 6, figs. 7–10, and pl. 7, figs. 1–2.
- Elphidium frigidum* (Cushman, 1933), Buzas, Culver and Isham, 1985, p. 1084, pl. 7, figs. 3–6.
- Elphidium subarcticum* (Cushman, 1944), Buzas, Culver and Isham, 1985, pp. 1083–1084, pl. 8, figs. 1–2.
- Elphidium* spp.
- Epistominella* sp.
- Fissurina* spp.
- Islandiella* spp.
- Lagena* spp.
- Nonionella stella* Cushman and Moyer, 1930, Cushman and McCulloch, 1940, p. 1962, pl. 18, fig. 2.
- Nonionellina labradorica* (Dawson, 1860), Cushman, 1930, p. 11, pl. 4, figs. 6–12.
- Quinqueloculina stalkerii* Loeblich and Tappan, 1953, p. 40, pl. 5, figs. 5–9.
- Stainforthia* sp.
- Textularia earlandi* Parker, 1952. Parker, 1952, p. 458, pl. 3, figs. 10–11.

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APPENDIX

Taxonomic Notes

The following list describes those taxa identified in this study. The listing provides a reference to which our species concepts are based, rather than the original reference for that species.

Identification of jumbo core material was done by Ullrich, who compared specimens with holotype, paratype, and/or hypotype specimens under a light microscope at the Smithsonian Institution. Research on the multicores was done by Zellers, who did not have access to type material. Due to similarities among these taxa, differences in our species concepts, and the fact that

PLANKTIC SPECIES

- Globigerina bulloides* d'Orbigny, 1826, Saito, Thompson and Breger, 1981, p. 40, pl. 7.1, fig. 1.
- Globigerina quinqueloba* (Natland, 1938), Srinivasan, 1975, p. 143, pl. 1, fig. 12.
- Globigerinita glutinata* (Egger, 1893), Smith, 1963, pl. 2, figs. 26–28.
- Neogloboquadrina pachyderma* (Ehrenberg, 1861), Todd and Low, 1967, p. A19, pl. 5, fig. 22.
- Indeterminate planktics.